ARMY RESEARCH LABORATORY

An Unmanned Ground Vehicle for Mine Detection: Systems Integration Issues and Recommendations

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ARL-TR-1256

MARCH 1997

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Aberdeen Proving Ground, MD 21005-5066

ARL-TR-1256 March 1997

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Abstract

The U.S. Army Research Laboratory performed a series of pilot studies for the Countermine Division at the Night Vision and Electronic Sensors Directorate concerning how a mine-detection sensor suite might be implemented on a teleoperated unmanned ground vehicle (UGV). The studies addressed five areas: mobility, human factors, radio communications, the use of infrared cameras for remote driving, and options for attaching the sensor array to the UGV. This report describes the proposed countermine system, the issues identified by the studies, and recommendations concerning how such a system might be implemented.

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AN UNMANNED GROUND VEHICLE FOR MINE DETECTION: SYSTEMS INTEGRATION ISSUES AND RECOMMENDATIONS

1. BACKGROUND

In January 1996, the U.S. Army Research Laboratory (ARL) was approached by the Army's Night Vision and Electronic Sensors Directorate (NVESD) to provide consulting support to an effort to rapidly develop an unmanned mine detector for operations in Bosnia. ARL was selected for this task because of its expertise in unmanned ground vehicles (UGV), previous experience in integrating mission packages with UGVs, and a history of support to NVESD in robotics for countermine. It was also anticipated that UGV test beds at Aberdeen Proving Ground (APG) could be used to breadboard implementation concepts in programmatic parallel with the development effort headed by NVESD.

The development effort was envisioned as fast paced, delivering roughly 10 mine detector-equipped UGVs in about 5 months. The mine-detection equipment was conceptually based on a sensor package developed by Geo-Centers, Inc., under a previous NVESD research contract, although the actual supplier would be determined by a formal procurement. The high mobility multipurpose wheeled vehicle (HMMWV)-based UGV was to be equipped with a remote operations kit to Project Manager (PM)-UGV specifications.

A short description of the Geo-Centers research equipment is necessary to understand the conceptual sensor package of this effort. The Geo-Centers research device contained ground-penetrating radar (GPR) and metal detectors mounted in a frame roughly 39 inches square and 8 inches high. The research device was attached to the front of a pickup truck so that it was about 1 foot above the terrain. The pickup truck was driven slowly along the mine lane, and the sensor data were analyzed and monitored at a workstation in the bed of the truck and telemetered to a data acquisition station nearby. An infrared imager mounted atop the cab of the pickup was also part of the sensor suite. Because the system was for research only and all mines were inert, it was not important that the pickup truck was wider than the detector array and that people were aboard the pickup truck.

The system to be developed for the field is somewhat different. Its purpose is to assure that a stretch of road is free of antitank mines, so that traffic can use the road without concern for mines. It may work with other similar systems in echelon fashion to clear the entire width of the road. It will proceed at speeds as low as necessary for the sensors to meet criteria having to do with probability of detection and false alarms. When a mine is detected, the system will stop if necessary, mark the location, and notify a nearby crew to neutralize the mine. Because the mine-detection vehicle is intended to be the first vehicle to encounter these mines, it is at high risk of detonating a mine. To reduce the hazard to personnel, this vehicle is to be unmanned.

The system is envisioned as comprising the following:

- The sensor analysis workstation is in a manned HMMWV (the "chase vehicle") which follows the sensor-equipped UGV at a distance of a few hundred meters, connected by a live video link and control link for driving and a telemetry link for monitoring of the sensors. (All communications links are assumed to be radio frequency.) The manned HMMWV has a second workstation for driving the UGV.

- The UGV is a HMMWV that is equipped with a teleoperation package consisting of a video camera (or other imaging sensor) to provide a windshield-equivalent view of the road; actuators for the driver's controls (foot pedals, shifters, steering wheel, etc.); and communication links to the driving workstation on the chase vehicle.

- The sensor package is an array attached to the front of the UGV, roughly 3 feet deep (along the axis of the HMMWV) and wider than the track of the HMMWV (which is 85 inches wide). Signal-processing equipment travels with the array aboard the UGV and feeds processed sensor data through a communications link to a workstation aboard the chase vehicle. The processed sensor data may also be available for real-time decision making aboard the UGV.

ARL's initial tasking was to perform a quick albeit non-definitive evaluation of issues regarding integration of the countermine mission package with a UGV. No external funding accompanied the initial request from NVESD so in-house resources were reprogrammed to support a limited scope effort. ARL quickly identified a number of mission-critical issues and applied its experiences with past UGV projects along with analysis and special experimentation (limited by cost and schedule) to provide the customer with a "first cut" at answers to his or her questions.

At the time of this writing, the project has not been funded, so the ARL effort has ceased. As a consequence, the recommendations of this document are preliminary and provisional. However, the effort invested in identifying these issues is significant, and the conclusions provide a basis for further investigations when the time is right.

2. APPROACH

ARL's effort included the following:

a) Under the supervision of knowledgeable personnel from NVESD, a small mine lane was installed as part of ARL-ATC's Robotics Test Course (RTC) at APG. The ARL team observed the emplaced mines using infrared (IR) imagery from an Amber IR camera to replicate imagery used by part of the Geo-Centers sensor package.

b) ARL personnel spent a number of hours remotely driving the Robotics Test Bed (RTB) on the RTC using imagery from the Amber IR imager. The RTB was driven on the gravel roads of the flat, grassy test course at 0700, 0900, and 1400 on a cold, sunny day in February. Videotape of imagery was collected as well.

c) The ARL team spent a limited amount of time at NVESD and on the telephone with the Geo-Centers team to try to understand as much as possible about the Geo-Centers experimental apparatus. They also visited a demonstration of several mine-detection experimental apparati at Fort A.P. Hill, Virginia, and participated in several meetings with NVESD and PM-Countermine discussing envisioned use of the system.

d) The ARL team designed and built a mock-up sensor array, attached it to the ARL RTB, and drove it remotely on the RTC. While the total remote operation time was approximately an hour, it resulted in a number of insights into driving with an attached array.

e) An analysis of the swept area of a vehicle-mounted array was conducted using the graphics capabilities of the IDEAS™ package. A parallel effort used analytical geometry in combination with understandings from motion planning for vehicle-like robots and the Maple® V software package for plotting.

3. RESULTS AND DISCUSSION

3.1. <u>Mobility</u>

3.1.1. *Speed*

The research sensor array is reportedly effective only at speeds below 1 or 2 mph and is sensitive to variations in road speed. It has been tested only to 1 km/hr (0.6 mph). Tight speed control at this low speed is outside the current design envelope of the ARL RTB and is a design requirement for teleoperated or autonomous operation.

Geo-Centers has reportedly proposed an upgrade of the signal processing used in the research equipment, which would allow speeds as great as 5 mph.

3.1.1.1. Cruise Control

A simple experiment to assess the ability of an operator to drive a UGV at very low speeds was performed by ARL's HRED Soldier-System Control Branch. An experienced UGV operator attempted to teleoperate the RTB vehicle at 2.5 to 5 mph on the level gravel roadways of ARL's outdoor Robotics Test Course. The UGV was driven from the ARL (HRED) command vehicle, which uses a joystick as the input device for UGV speed control. Speed was read from the operator control readout, a digital display driven by the HMMWV speedometer sensor. No quantitative measurements were recorded, but the following qualitative assessments were apparent: (1) The operator could not maintain a steady speed for any significant period of time (1 minute) using the joystick speed control; (2) the effort of controlling speed was a substantial component of operator workload.

In a subsequent trial, a cruise control function implemented in the UGV software was able to control UGV speed at about 2.5 mph. A "cruise control" function seems a necessity for the countermine application.

3.1.1.2. Brakes-on Speed Control

The idle ground speed of a ground vehicle is the product of engine idle speed times end-to-end gear ratio times wheel circumference. This is the speed at which the vehicle will travel on level terrain over a reasonably smooth surface, with the engine at idle. In low gear, low range, at 650 rpm, an M1097A2 HMMWV travels at 2.02 mph (2.38 mph in reverse). This road speed is the maximum proposed for the application. The implication is that speed control for the HMMWV will require control of the brakes more than control of the accelerator. The HMMWV will thus operate with brakes applied continuously, potentially for hours at a time. This is outside the normal operating envelope of a HMMWV. Two problems are apparent.

One problem is that the control loop of the ARL RTB and other known HMMWV-based UGVs are optimized for approximate control of speed at low to high speeds, but not at the extremely low speeds of the application. Further investigation of control issues is necessary to determine how to best achieve the close tolerance speed control required using braking actuation. It is believed that speed can be controlled successfully on reasonably smooth roads by tuning the control system, a reasonably simple process. This approach was used in a past exercise to enable the ARL UGV to descend hills in a controlled fashion. The robustness of this approach in the context of the application needs to be evaluated and confirmed.

A second problem is that the HMMWV is not designed to be driven with its brakes applied continuously. This concern was raised informally to personnel of the Tank-Automotive Research, Development, & Engineering Center (TARDEC)'s HMMWV engineering group and independently to personnel of AM General, the manufacturer of the HMMWV. The informal assessment of both was that there is probably not a problem at the low speeds envisioned. Brake pad wear may be greater than normal, requiring more frequent pad changes, but brake overheating was not expected. Engine and/or transmission overheating from inadequate air flow over the radiators was also possible but unlikely. ARL has experienced problems in the past from overheated power steering fluid when older HMMWVs are run at idle for periods of time, but the latest A2 HMMWVs are equipped with both power steering and transmission radiators. While no problems are anticipated, it makes sense to test for this vulnerability early in the program. A more formal request for TARDEC assessment of the proposed use of the HMMWV is recommended.

3.1.2. *Stopping Distance*

Upgrades of the signal processing proposed by Geo-Centers will, if successful, raise attainable ground speeds to around 5 mph, which will reduce dramatically the magnitude of the issues described in the previous section. Higher speeds will increase problems described in other sections, however. In particular, stopping distances will increase and dynamic loading of the array suspension will increase dramatically.

It is desirable for the UGV to stop before running a tire over a mine it has detected. The faster the ground speed of the UGV, the longer the stopping distance. It is unlikely that the trailing edge of the detection array will be more than 3 feet ahead of the axle. At 5 mph, stopping within 3 feet requires constant deceleration of approximately 1/3 gravity, a panic stop. It is not evident that the HMMWV is capable of such a rapid stop, especially given processing and actuation lags in the control system and that the road being swept provides less than ideal traction. A practical operating speed will have to be determined empirically before the HMMWV is deployed to the theater.

Even at 2 mph, the UGV traverses 3 ft/sec, so the time available to detect a mine and choose a course of action is no more than a fraction of a second. The short span of time available for this process makes it absolutely necessary that the decision to stop or avoid the mine be made as rapidly as possible. Human reaction time, 200 ms or more, is likely to be a dominant factor in stopping distance. If the signal processing of the sensor subsystem detects a mine, it must be able to command the UGV to stop without waiting for the concurrence of a human operator. Similarly, if the operator detects a mine, he needs to be able to command a stop independent of the sensor subsystem.

It may be possible to steer around a mine during braking, allowing more time for deceleration to a stop and thus higher operating speeds. A path-planning concept for steering among multiple mines was modeled at ARL, but results are not available at this time.

3.1.3. *Steered Wheels Behind (SWB) Driving Mode*

When a four-wheel vehicle with Ackerman steering executes a turn, its front and rear wheels follow different paths. The smaller the radius of the turn, the greater the difference in the paths of the front and rear wheels. The consequence of this in a mine-detection scenario is that the rear wheels may traverse terrain that has not been swept by the detection array (see Figure 1), terrain that may contain undetected mines.

One way of reducing the problem is to mount the detection array on the back of the HMMWV and drive the HMMWV in reverse. Driving in reverse will hereafter be called steered wheel behind (SWB), as opposed to driving in forward gears, or steered wheel forward (SWF) (see Figure 2). While SWB operation is not practical for a conventional HMMWV because the driver's seat is oriented for an SWF configuration, SWB configuration is common in forklifts and has specific benefits for precise positioning of loads when maneuvering space is restricted. SWB is quite easy to implement on an unmanned HMMWV because of the "virtual" connection between the steering wheel and the steered wheels. By installing the driving camera pointing rearward, electronically reversing left and right at the steering wheel, and adding modest visual cues, it can be made nearly transparent to the operator that he is driving SWB. Subsequent references to SWB assume these modifications. Also, when referring to a SWB vehicle, the meanings of "front" and "back" are inverted as are "forward" and "reverse" (e.g., the radiator of an SWB HMMWV is in the "back").

The benefits of using SWB with a rear-mounted array will be explained in more detail.

3.1.3.1. Mounting Points

Mounting points for a front-mounted array are limited. The HMMWV is designed to serve as an SWF, man-aboard truck. Its load is assumed to be carried in the bed. Consequently, there are few useful "hard points" forward of the fire wall except on the "bumper" and frame rails, and the sling attachment points. Accessories mounted on the front of a HMMWV must be designed not to interfere with regular maintenance of the engine, because of the manner in which the hood tilts forward for engine access.

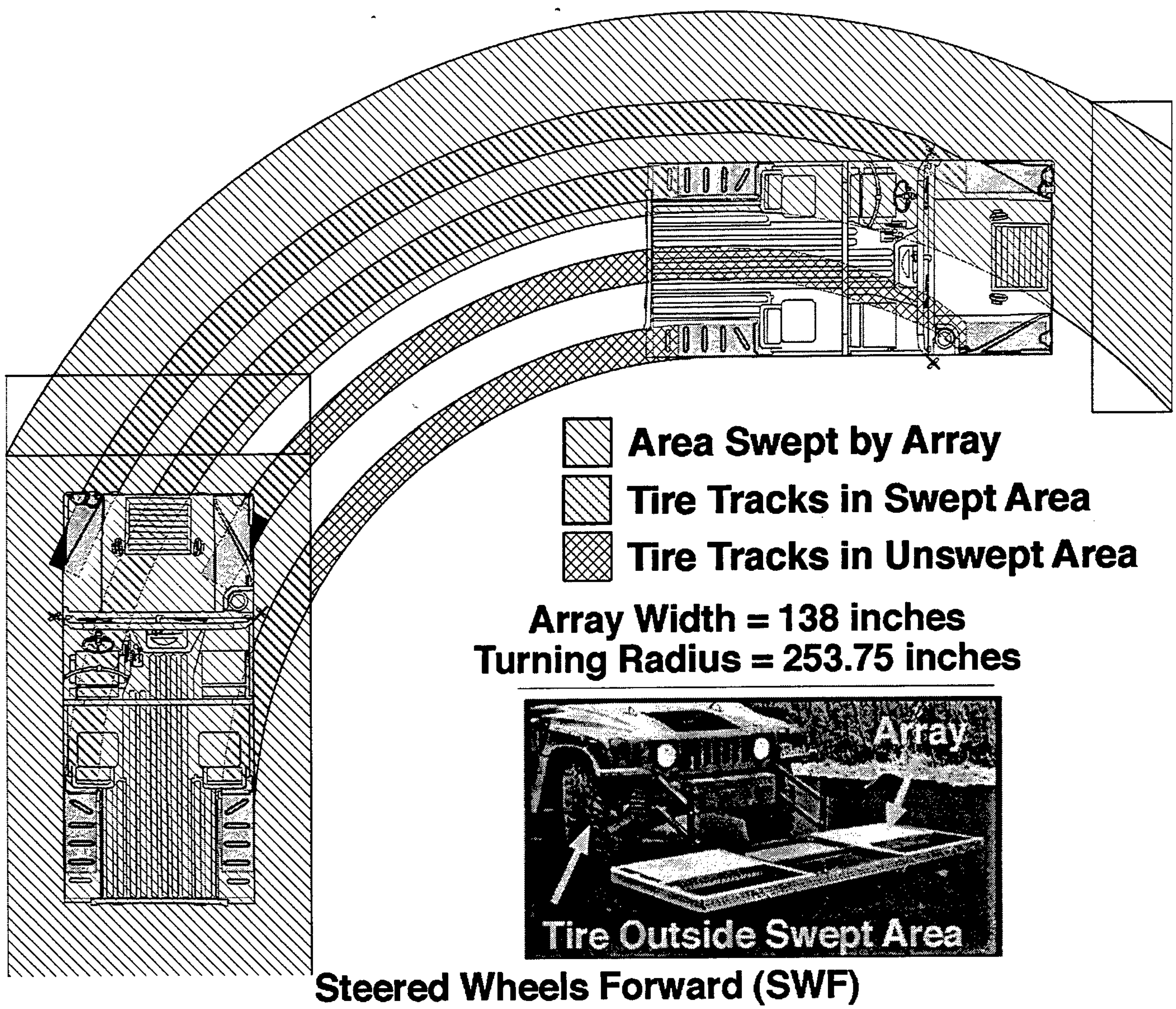

Figure 1. Wheels Traverse Unswept Terrain.

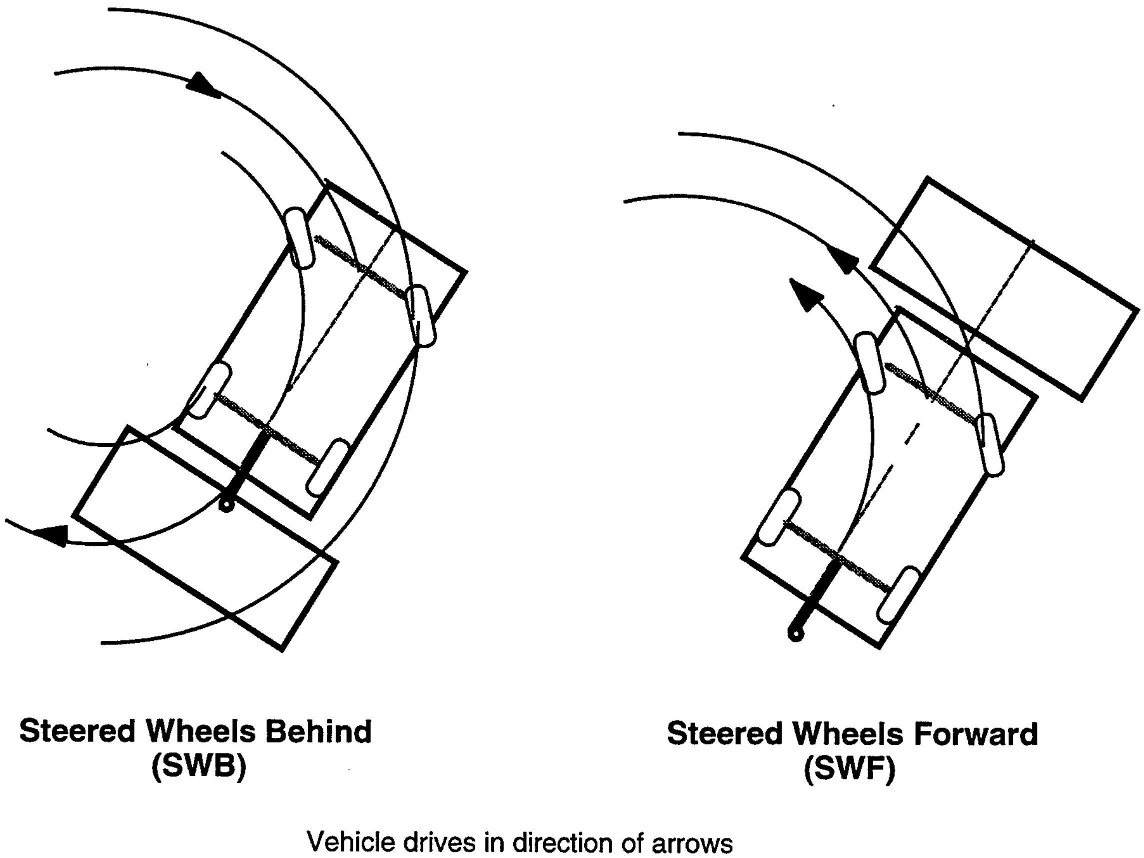

Figure 2. SWB Versus SWF.

In the bed of the HMMWV, there are eight tie-down locations rated at 2,500 lb each. The capacity is probably even higher if loads are secured by the bolts holding the tie-down retainers, rather than by the retainers themselves. Six of the tie-down locations form a rectangular constellation 50.81 inches along the centerline of the vehicle and 45.04 inches across (see Figure 3). These attachment points can be used to locate a structure in the bed of the vehicle capable of absorbing much dynamic load from a cantilevered sensor array, yet requiring no alteration of the vehicle structure.

3.1.3.2. Stowage

A rear-mounted array can be designed to be stowed in the bed of the HMMWV without mechanically removing it, for transit to and from and between work sites. A front-mounted array must be detached for transit. This can reduce availability of the equipment. The rear-mounted array is also better suited to short-duration, road-speed, man-aboard transits with the array in place, as between nearby work sites, or emergency extraction beyond range of sniper fire.

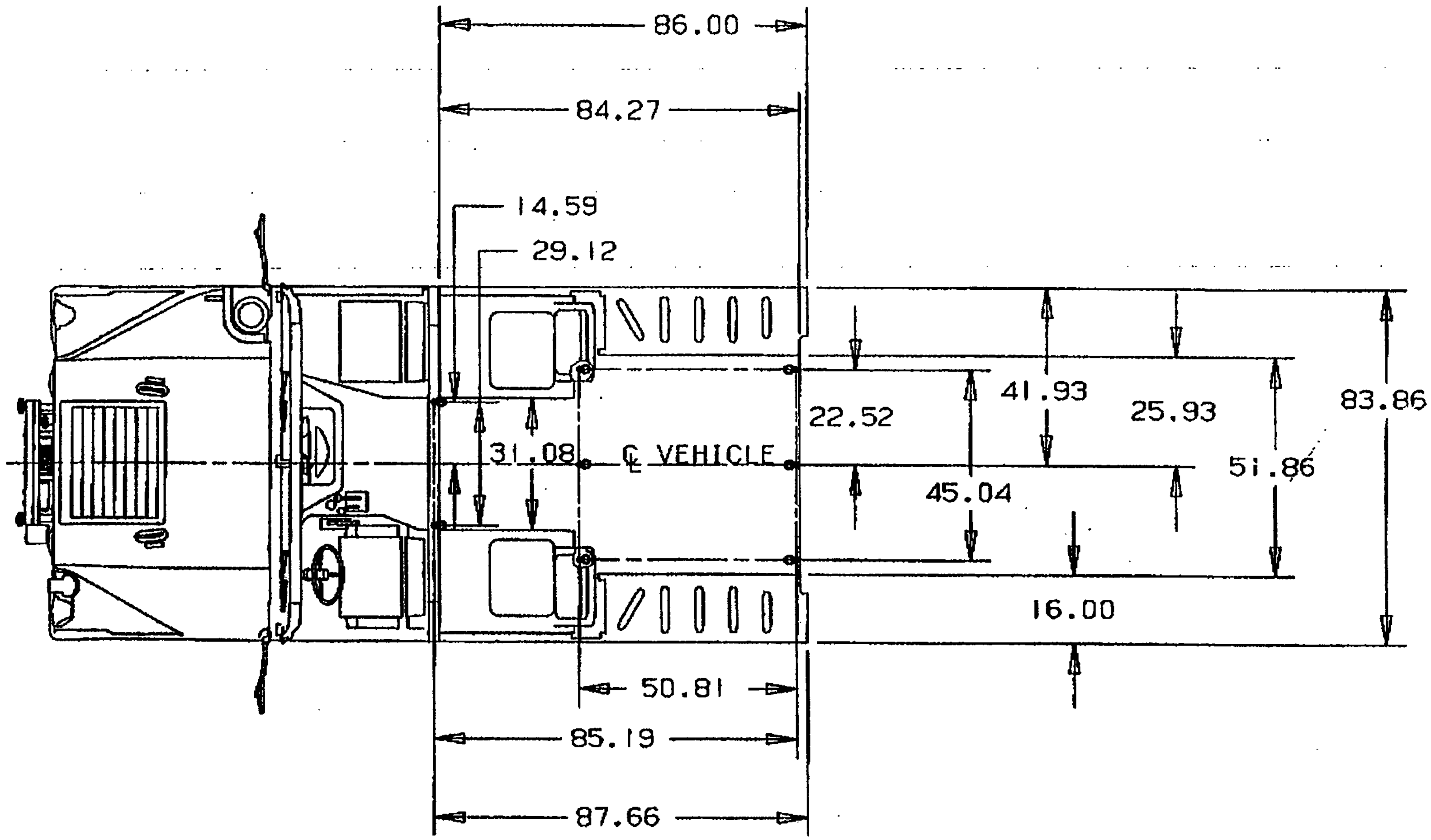

Figure 3. Tie-down Locations and Cargo Area for Four-Man M1038 w/w M998 wo/w Cargo Troop Carriers.

3.1.3.3. Array Size

The width of a sensor array required to provide a swept area for the wheels of the truck is a function of the driving modality (SWF or SWB), the radius of the sharpest turn to be executed, truck wheelbase and width, distance from the rear of the array to the nearest axle (termed "offset"), and array depth (dimension along the centerline of the truck). Once a vehicle is selected as a platform, the vehicle wheelbase and width are fixed, so only the driving modality, array offset and depth, and turn radius remain as variables. Array offset is presumably to be minimized to mitigate cantilever effects. Since the array depth is fixed by the detection technology, array width is a function of the turning circle of the truck to a first approximation.

An analysis of vehicle steering geometry reveals that SWB driving offers substantial benefits over SWF. An array similar to the Geo-Centers array could cover the track of an SWB HMMWV at full steering lock (about 45 feet curb to curb) with an array width of roughly 140 inches. This is only slightly wider than the 3-meter (120-inch) array width originally suggested by NVESD personnel. In an SWF configuration, an array exceeding 460 inches wide is required. A 140-inch-wide array on an SWF HMMWV would allow only shallow turns of 124 feet curb to curb (see Appendix A).

3.1.3.4. Drivability

In a previous collaboration between ARL and NVESD, HMMWV-based UGVs were teleoperated in SWB mode at speeds of 5 to 10 mph during testing of the Off-Road Smart Mine Countermeasures (ORSMC) UGV. The operators reported no problems with operating in this mode. These drivers were exercising road-following activities, whereas operators of a mine-detection UGV will also need to evade mines in the roadway, a somewhat different task. When an SWB vehicle executes a sharp turn, the back (steered wheel) end can deviate substantially from the path apparent in the driver's view. In tight quarters or on a very narrow road, this could cause the "rear" of the truck to strike objects alongside the road. However, the act of steering the "front"-mounted array of an SWB vehicle assures a clear path for its "rear."

To assess the suitability of the SWB imagery for driving, ARL mounted a mock-up detector array on the back of a UGV and reversed the roll bar-mounted driving camera. With the standard 56° horizontal field of view (FOV) camera, and using traffic cones on the corners of the mock-up to emphasize the edges of the array, the static image appeared adequate for driving purposes. In an abbreviated test, one experienced and one inexperienced UGV operator successfully drove the UGV at low speeds on the one-lane gravel roads of the ARL-ATC RTC.

Tasks completed included road following, sharp turns, and maneuvers between barrels spaced approximately 130 inches apart (the array itself is 117 inches wide). While it was not really "transparent" that the UGV was in SWB mode, it was no more difficult to drive in this mode than to drive a UGV in SWF mode. Optimization of camera location and array edge cues could probably provide marginal improvements to drivability. The overall assessment is that SWB driving mode for low speed operation is viable for UGV driving.

3.2. Human Factors

Remote operation of the countermine-equipped UGV has two components directly involving soldiers: 1) driving the UGV, and 2) analyzing displays representing output of the countermine sensors. It is assumed that the soldier driving the UGV and the soldier analyzing the sensors will ride in the chase vehicle, which is driven by a third soldier. ARL's preliminary evaluation of human factors issues in this way of doing things identified three areas of special concern.

First, assuming similarity to the Geo-Centers experimental apparatus, the sensor analyst must interpret IR imagery and radar imagery from the entire array, cued by audio warnings from the metal detectors. The workload of this task has not been formally assessed but may be significant, as it appears to involve recognition of patterns in rapidly changing, unfamiliar imagery. The sensors team should seek approaches to simplifying this task. It is desirable that the detection of mines in the imagery be primarily a function of the sensor-processing computers, with the operator providing oversight and anomaly resolution. The sensors team should also take any opportunity to emphasize the relationship between elements of one display and elements of the other, perhaps spatially or by a shared highlighting scheme (for example, the green area in the IR imagery corresponds to the green area in the radar imagery). It is even possible that a second sensor analyst will be necessary to reduce the workload to appropriate levels. The ARL team can make more specific recommendations when a full task analysis has been conducted.

Second, the extremely low speed operation of the UGV introduces an element of tedium to all three jobs in the chase vehicle. The sensor analyst(s) and to a lesser extent the UGV driver will be asked to perform what is essentially a vigilance task. It is well established that humans are not well suited to vigilance tasks (Boff & Lincoln 1988). To improve operator performance in such tasks, it is common to introduce "cueing" (alerting the operator to display elements requiring his immediate attention, perhaps by highlighting portions of the imagery having suspicious characteristics). The sensors team needs to seize any opportunity to provide cueing to the sensor analyst to focus his attention on specific phenomena requiring his special attention.

Third, the soldiers sharing the chase vehicle need high quality, structured communication among themselves. If the sensor analyst spots a mine, he has to have a well-understood mechanism for assuring that the UGV driver does not drive the UGV over it. If the UGV driver sees a suspicious spot ahead, he has to have a way to bring it to the attention of the sensor analyst, and the driver of the chase vehicle has to know where the mines are that have been located by the sensor analyst, to avoid the terrible possibility of the chase vehicle being destroyed by a mine that was detected by the UGV.

3.3. Radio Frequencies

Geo-Centers has discussed using spread-spectrum radios in the 900-MHz commercial band for all communications, including IR imagery, between the UGV and the control vehicle. It is not clear from the documentation provided by Geo-Centers, but it seems likely that more than one channel (of the seven available using the radio used by Geo-Centers) is needed. This frequency band is also a candidate for the UGV control radios, requiring two additional channels. Video from the driving camera would likely use a separate band higher in the frequency spectrum. Some efficiencies can probably be achieved by consolidating message traffic on underused channels in the commercial band. However, the commercial band is quite busy (at least three channels and possibly twice that) with one UGV and may be inadequate for the user's stated desire to operate these vehicles in echelons. Furthermore, there has been mention of the possibilty of operating these UGVs in formation with armored UGVs clearing anti-personnel mines, which makes further demands of the RF spectrum.

Approval to use specific radio frequencies must be cleared by the appropriate authorities in Bosnia (or wherever these systems might be deployed). Initial inquiries by ARL were not definitive, but knowledgeable personnel with experience in frequency allocation in Europe have expressed confidence that the desired frequency bands are generally available in Bosnia at the power levels envisioned for UGV countermine applications.

3.4. IR Cameras

An IR camera focused on the roadway is an element of the mine-detection suite. ARL did a quick evaluation of the feasibility of using this camera for driving the UGV, as well. The IR imager was built by Amber, Inc., and used a 30° FOV lens. This lens was the only one available and was not optimized for driving or mine detection.

Benefits envisioned were (1) the UGV driver could look for mines while he was driving; (2) night operations would be possible; and (3) only one high bandwidth, imagery-capable radio channel would be necessary, instead of two.

3.4.1. *Driving*

The UGV was driven on the ARL-ATC test course at speeds from 2 to 15 mph using the Amber "Radiance™ 1" IR imager (see Figure 4) as the sole source of windshield-equivalent imagery. The FOV was too narrow for confident cornering (56° is considered minimum for this application), but the imagery was completely adequate for driving in February from early morning to mid-afternoon, with an experienced UGV driver on familiar terrain. The testing was not definitive, but no evidence was discovered of limitations to daytime driving using IR imagery.

During daylight hours, differences in solar absorption cause temperature differentials that are apparent in the IR imagery, such as between dirt or gravel roads and surrounding fields. These differences are used by the UGV driver to identify and track the road edge. These differences fade, however, as temperatures equilibrate, a condition known as thermal crossover. At these times, the IR imager provides its poorest performance. Thermal crossover would be expected to impair the driver's ability to follow the road. This is probably not a significant shortcoming for this mission, however. Since thermal equilibrium also minimizes thermal contrast between mine and road, it seems unlikely that the system would be used in unmanned mode during these times.

The operator must keep in mind that when he is driving by an IR imager, it is not a visual sensor. IR imagery is based on differences in temperature, not reflected light. Things that stand out with high contrast in the visual world are not the same as those that stand out with high contrast in the world as presented by an IR imager. Because of this, the operator must be trained in the use of IR imagery. An operational scenario should include a driver orientation period at the beginning of each day's mine-sweeping runs. This orientation period consists of a short run on a road similar to the one he will be operating on that day, with similar terrain, weather, and shading conditions. This will allow the operator to stop when he does not recognize something on the IR image and visually check it to develop a visual-image-to-heat-image relationship. To support this capability, the UGV must also have a visual imager (video camera) close to the IR imager, so the operator can switch back and forth between the two images as needed.

Amber's **Radiance™ 1** is a portable, high-performance, mid-wave infrared (MWIR) camera system ideal for a wide variety of thermal imaging requirements. The camera is specified for Imaging in the broad band MWIFR region from 3.0 to 5.0 µm and has demonstrated excellent night and thermal vision.

The 256x2S6 element MWIR detector array construction is based on hybrid focal plane array (FPA) technology. Indium antimonide (InSb) detectors are interconnected to an advanced CMOS integrated circuit. The InSb hybrid format provides the highest sensitivity available in a mid-infrared camera.

The camera, including power supply, measures 4.S"W x 7"H x 9.5"D and operates over a DC range between 20 to 32 volts. The advanced, 'sensor engine' is a high-reliability, long-life, qualified subassembly. A sophisticated digital signal processing (DSP)-based acquisition and imaging electronics system that supports real-time image enhancement is incorporated Into the camera. The resulting imagery has TV-quality resolution.

Simple operating controls provide a convenient user interface. Optionally, extended capabilities of the camera can be accessed by remote control through an RS-232 interface. A menu-driven program is supplied that currently supports over 100 camera commands. This program provides a general level of interaction along with applicable help features.

The executable programs operate on PC-compatibles. The supplied programs allow macro files to be generated and stored for simple command and control missions. 'C' source code libraries are also provided which allow users to custom program command and control functions of the Radiance camera in the PC environment.

Multiple analog and digital outputs are furnished, including RGB AS-170A, NTSC or PAL, S-Video, and 12-bit digital. Internal, automatic calibration sources are for normalization of the sensor, enabling completely unmanned remote operation.

The Radiance camera accommodates quick-connect/disconnect bayonet mount lenses. No special attaching hardware is required. Several fixed focal length lenses are offered, including 25mm, 50mm, and 1 00mm. A dual field of view lens is available that provides the user with a wide field focal length of 75 mm, and a narrow field of 250 mm. DFoV lens control is available through the camera control computer.

Figure 4. IR Imager Specification Sheet.

3.4.2. *Mine Detection*

The IR imager was focused on several antitank mines newly emplaced in the test course to assess the ability of an operator to detect the mines in the imagery while driving. During the test, the mines looked no different from the surrounding gravel roadway, and the driver could not see them even when stopped and told where they were. This was unexpected, as Geo-Centers videotape of mine lanes, using an IR imager in the 3- to 5-micron band, showed the mines quite distinctly.

The ground and gravel roadway at the time of the test were frozen solid, a consequence of a wet, cold February. While the sun shone brightly during the test, it did not thaw the ground beyond half an inch or so. This seems the likely cause of the unexpected results. While the test was unsuccessful in answering the question it had intended to answer, it did identify an anomalous condition unexpected by the test crew and of potential significance to a system deployed to an area with Bosnia's climate.

3.5. Array Suspension

Suspension of the sensor array from the truck frame may be accomplished in several ways. The means of suspension is more a function of the sensor technology, which is not the expertise of the ARL team, than of the robotics implementation. However, in addressing the robotics issues, the ARL team identified several issues that need to be handled by the sensors team.

3.5.1. *Cantilevered Versus Suspended*

The sensor array must be "flown" over the road surfaces in one of two ways: by cantilevering the array from the front of the truck or by suspending it from wheels mounted on the front of the array. If wheels are used, they must have a radius large enough to assure mobility over potholes and rough surfaces, which implies a "large" wheel. The wheel must distribute the load over a large area to keep ground pressure low enough that the mines do not detonate, which tends to mean a wide wheel and possibly spring suspension. A gimbal mechanism enabling the wheel to turn as needed is massive in proportion to the size of the wheel. Without careful engineering and astute selection of materials, the gimbal and wheels will weigh more than the array, so suspending the array from wheels is not a desirable approach.

Cantilevering the array from the front of the HMMWV subjects the array to the bumps and shocks encountered by the HMMWV, multiplied by the lever arm which is the cantilever. Excited by these disturbances, the array flexes vertically at the natural frequency of the array. It is possible that this motion at critical ground speeds can coincide with characteristic dimensions of the mines being sought, causing false alarms. At low speed, the HMMWV suspension appears adequate to damp much of the shock load, but this bears investigation. The response of the array structure, excited by HMMWV motions from road surfaces such as those in the field, should be modeled and tested early in the program.

3.5.2. *Accommodation of Grade Changes*

An array rigidly cantilevered from a vehicle assumes the pitch of the vehicle. If the grade of the road changes markedly at some point (possibly at an intersection with a crossroad), the forward-mounted array will encounter the grade change before the vehicle does, affecting the ride height of the array. The mine-detection sensors are reportedly sensitive to ride height, so their effectiveness may be compromised by changes in road grade. If the grade change is substantial and if the cantilever is large, the array may even touch the ground, causing physical damage. (The ARL team discovered how easily this could happen during remote operation with the array mock-up on the Robotics Test Course.) Some mechanism to adjust ride height seems essential.

One way to control ride height is to raise and lower the entire array without altering the pitch. A drawback of this approach is that the leading and trailing edges of the array are not at the same ride height when road grade is changing.

Another approach is to hinge the array at its attachment point to the vehicle and change the pitch of the array with respect to the vehicle. Thus, pitch control governs the ride height of the leading edge of the array and the trailing edge rides at the ride height of the vehicle. This appears easier to implement and is consistent with the array suspension on the Geo-Centers experimental device. ARL has begun conceptual designs on such a suspension. The following discussion assumes a cantilevered array suspension hinged at the point of attachment to the vehicle.

Because grade changes can occur during a mission, it is desirable that the ride height be changed remotely to avoid unnecessary exposure of troops to mine hazards. Thus, the ride height of the array should be actuated and controlled either from the chase vehicle or in closed loop by means of height sensors on the leading edge of the array. Height sensors are important because the UGV operator cannot easily determine the ride height by looking at driving imagery.

3.5.3. *Accommodation of Road Contour*

Real-world roads in the U.S. are typically crowned, that is, the middle of the road is higher than the sides. If this practice is common in Bosnia, and if the tolerance on the ride height of the sensor array is sufficiently small, it may be necessary to configure the sensor array in panels rather than in a single unit, as in Figure 5. The panels, hinged along the axis of travel of the UGV, will have to be reconfigured, depending on the contour of the road at hand. If the contours are not consistent over a stretch of road, the sensor panels may have to be reconfigured from time to time during the traversal of the route. Furthermore, if the ride height band of the sensor array is sufficiently narrow, the panels may have to be reconfigured dynamically, based on ride height sensors, increasing the complexity of the design and the weight of the array, which in turn complicates the design of the array suspension.

Information from the user concerning the geometry of the roads that he or she wants to use this system on must be gathered while the design is yet fluid. However, a best guess is that the contour will remain reasonably consistent for hundreds of meters (tens of minutes) at a time but not necessarily for an entire day's activity. It would be least hazardous to chase vehicle personnel if the changes in panel configuration could be accomplished from the chase vehicle. A best guess recommendation is that the panel configuration should be remotely configurable by means of servo motors but not slaved to sensors. This recommendation is of course tentative and depends on the actual operating characteristics of the sensors and the actual terrain to be swept for mines.

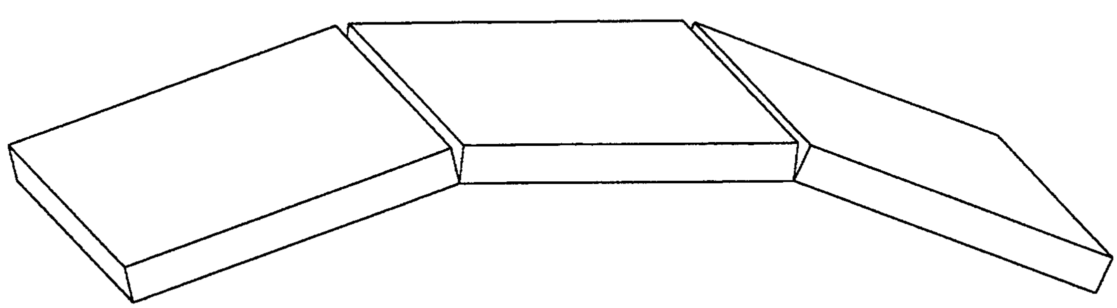

Figure 5. Three-panel Array.

4. RECOMMENDATIONS AND PRELIMINARY CONCLUSIONS

4.1. The sensor array should be mounted on the back end of the UGV, with the UGV teleoperated in reverse from a rear-looking camera (termed "SWB" in the text). The primary reason for this approach is that only this configuration allows a reasonable-sized sensor array to sweep the entire width of the UGV track while retaining reasonable maneuverability. Other benefits include the availability of mounting "hard points" and stowage in transit.

4.2. The effective width of the array should be at least 130 inches and preferably, 140 inches. A 140-inch-wide array in SWB configuration will detect mines across the entire track of the HMMWV, even with the steering at full lock.

4.3. Design elements should be capable of operating at ground speeds of 5 mph. Speeds are currently limited by signal processing of the detection array system. Application of computing technology will reportedly relax this bottleneck. However, higher ground speeds will demand a more capable array suspension system. The maximum safe speed must be determined experimentally, but it is clear that speeds exceeding 5 mph will not allow the UGV to stop before running over the mine it has detected.

4.4. The UGV must have a form of closed loop speed control using braking action to control vehicle speed below 3 mph. Testing of the effectiveness of this approach should occur early in the development process, as it is a critical capability. Testing should also include individual tests of sufficient duration to evaluate the effect on the temperatures of brakes, brake fluid, power steering fluid, and engine coolant, of running at low speed for hours at a time.

4.5. A communication architecture for communications between the UGV and its chase vehicle must be established early, requiring coordination between the UGV team and the sensor team. Approval to use specific radio frequencies must be coordinated with the appropriate authorities in Bosnia, and the intended use of the UGVs must be discussed with the user to clarify interference issues resulting from the operation of several UGVs in proximity.

4.6. The UGV should be equipped with a video camera for driving in addition to the IR imager used for mine detection. If communications limitations require the two to share a single video communication link, the UGV driver can probably drive using IR imagery most of the time. However, he or she will occasionally need to be able to switch to video imagery to clarify puzzling images from the IR sensor and may sometimes need a wider FOV than optimum for the mine detection imager. If communication limitations allow, the best choice is to provide the driver with full-time access to a wide FOV color video image optimized for his or her driving requirements. Even in this case, a means should be provided to display the IR imagery to the UGV driver to enable night operations.

4.7. The array should be cantilevered from a structure bolted to the attachment points for the tie-downs in the bed of the HMMWV. The array should be hinged across the axis of travel, so that changes in road grade can be accommodated by changing the pitch of the array. The hinge joint should be close to the HMMWV chassis and the array depth kept small to minimize cantilever effects on ground clearance. Array ride height sensors should be mounted on the forward edge of the array to assist the driver in judging the need to change array pitch. The array suspension should be actuated and adjustable from controls in the chase vehicle or closed loop from the array ride height sensors.

4.8. The array should be made of three panels, hinged along the axis of travel of the UGV to control sensor ride height on crowned or contoured road surfaces. The panel configuration should be actuated and adjustable from controls in the chase vehicle.

4.9. Detection of mines in the sensor imagery should be a function of the sensor processing computers, with the operator providing oversight and anomaly resolution. The sensor analyst should be immediately alerted to possible detections (or other anomalies) by the sensor-processing computers. The displays in the chase vehicle of the various sensors should be integrated as tightly as possible, to assist the soldier in rapidly understanding the information being presented. The display should focus his attention on display elements that best correspond to the phenomenon being reported. The UGV should stop automatically when a high-probability detection is made, rather than waiting for confirmation by the operator.

4.10. The chase vehicle should have a communication system (intercom?) to assure communication among the soldiers operating the various elements of the UGV.

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REFERENCES

Boff, K.E., & Lincoln, J.E. (1988). "Engineering Data Compendium: Human Perception and Performance," pp. 1500-1501. AAMRL, Wright-Patterson AFB, OH.

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APPENDIX A

ARRAY WIDTH AS A FUNCTION OF SWF VERSUS SWB

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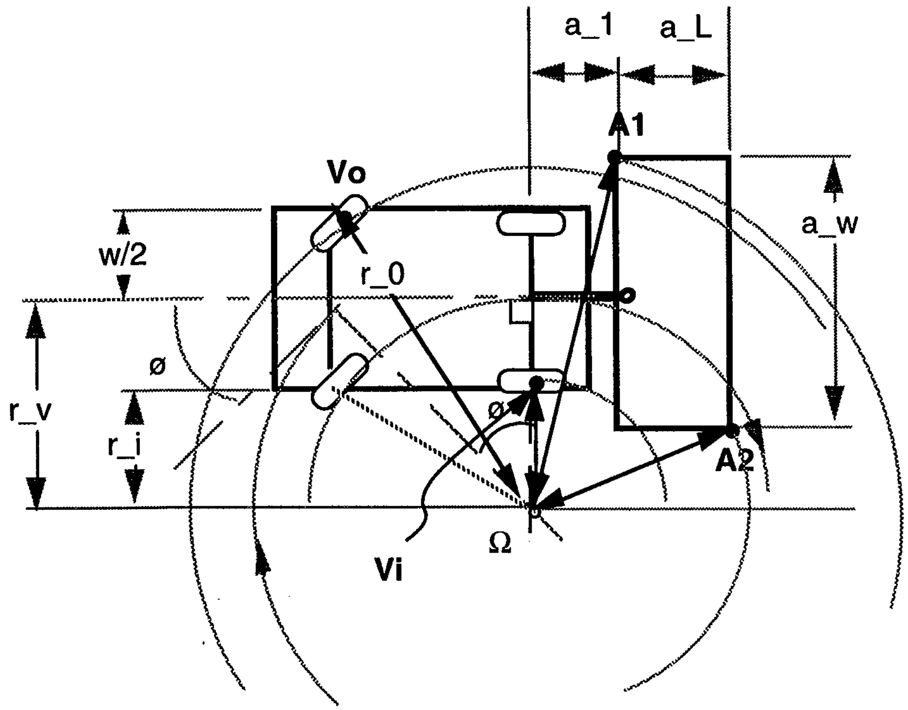


KEY

Ω = Rotional center of vehicle
A1 = Outermost effective trace of array
A2 = Innermost effective trace of array
Vo = outermost track of wheels
Vi = innermost track of wheels

r_v = radius of rotation of center of vehicle
r_o = radius of outermost track of wheels
r_i = radius of innermost track of tires
b = wheelbase of vehicle
w = width of vehicle
a_w = width of array
a_1 = distance from rear axle to array ("offset")
a_L = depth of array
ø = steering angle

Conditions for Safe Operation *

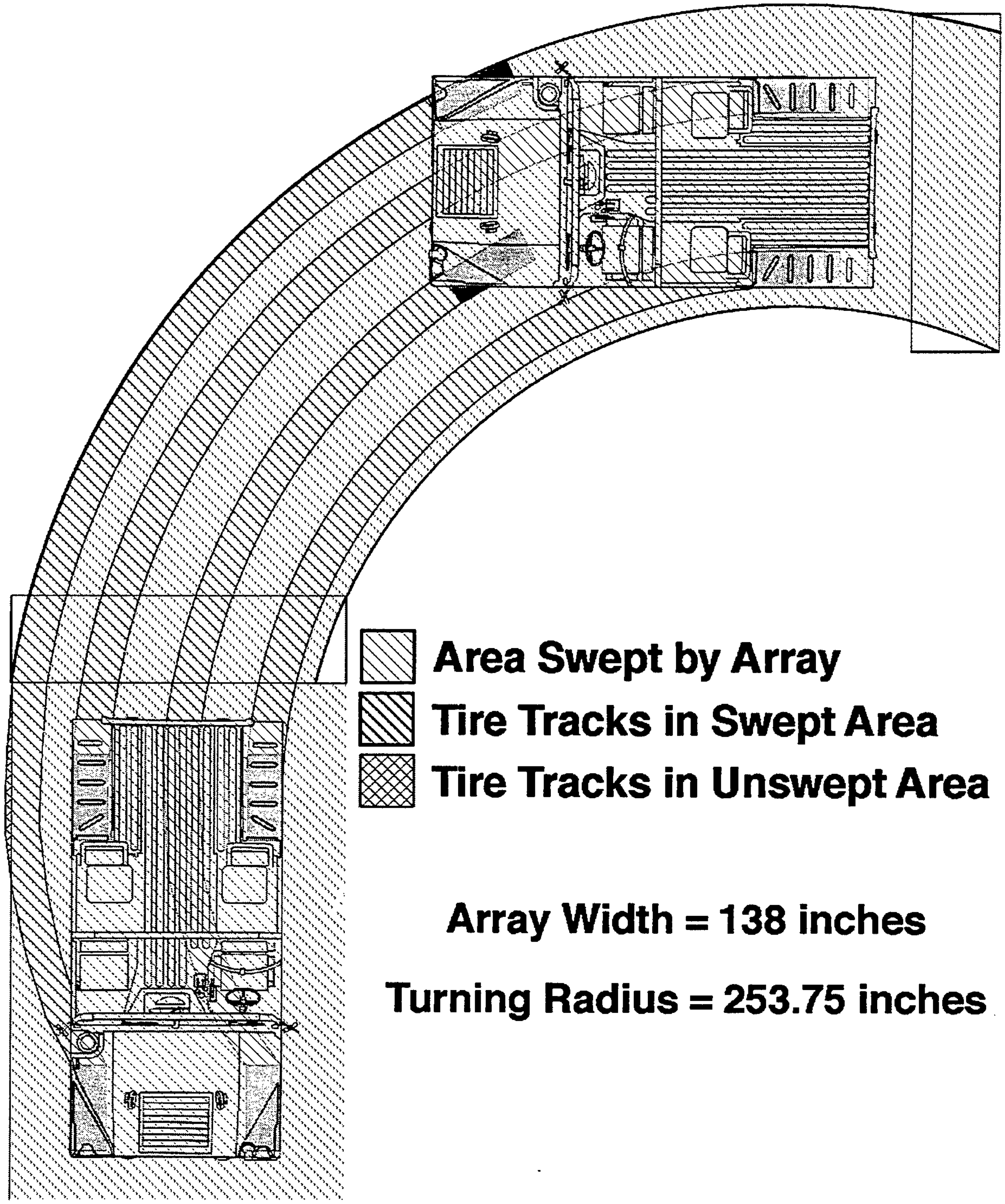
cond 1: $|\overline{\Omega\, A1}| > |\overline{\Omega\, Vo}|$

$$\cap$$

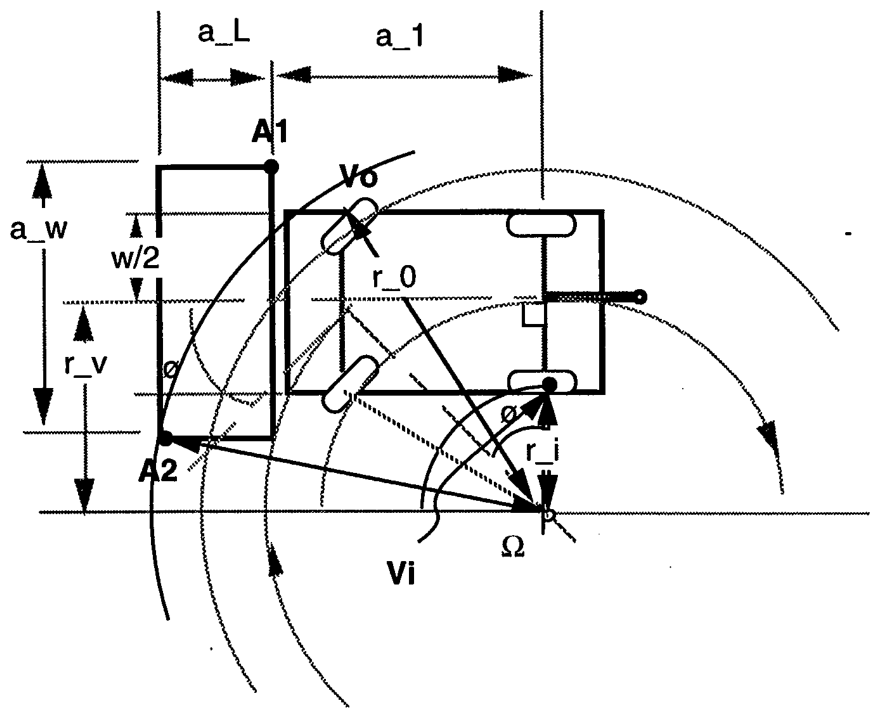
cond 2: $|\overline{\Omega\, A2}| < |\overline{\Omega\, Vi}|$

* Note that the drawing depicts an unsafe condition, violating condition 2

Steered Wheels Behind (SWB)



Steered Wheels Behind (SWB)



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A1 = Outermost effective trace of array
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Vo = outermost track of wheels
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r_o = radius of outermost track of wheels
r_i = radius of innermost track of tires
b = wheelbase of vehicle
w = width of vehicle
a_w = width of array
a_1 = distance from rear axle to array ("offset")
a_L = depth of array
ø = steering angle

Conditions for Safe Operation *

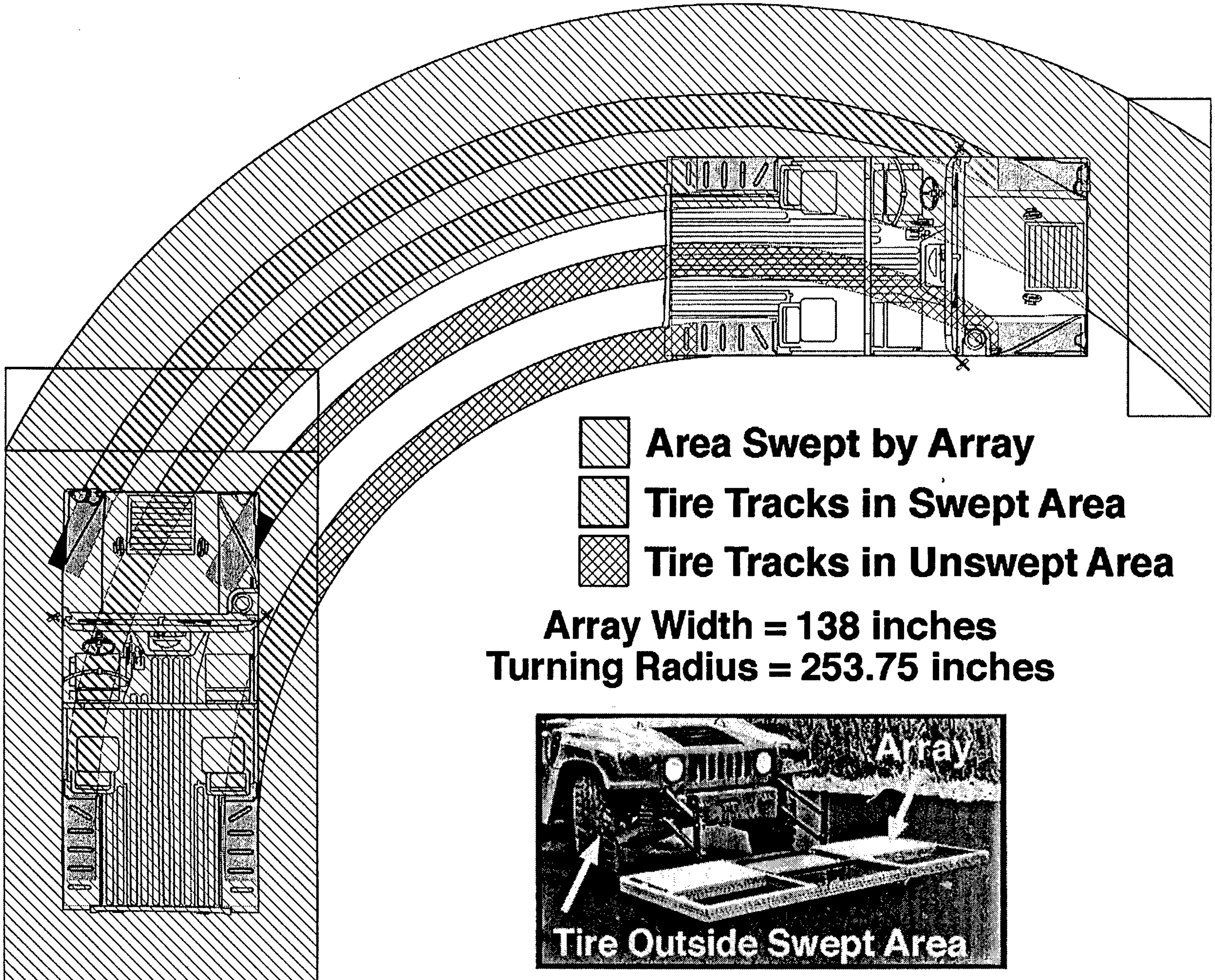
cond 1: $|\overline{\Omega A1}| > |\overline{\Omega Vo}|$ **(trivial)**

$\cap$

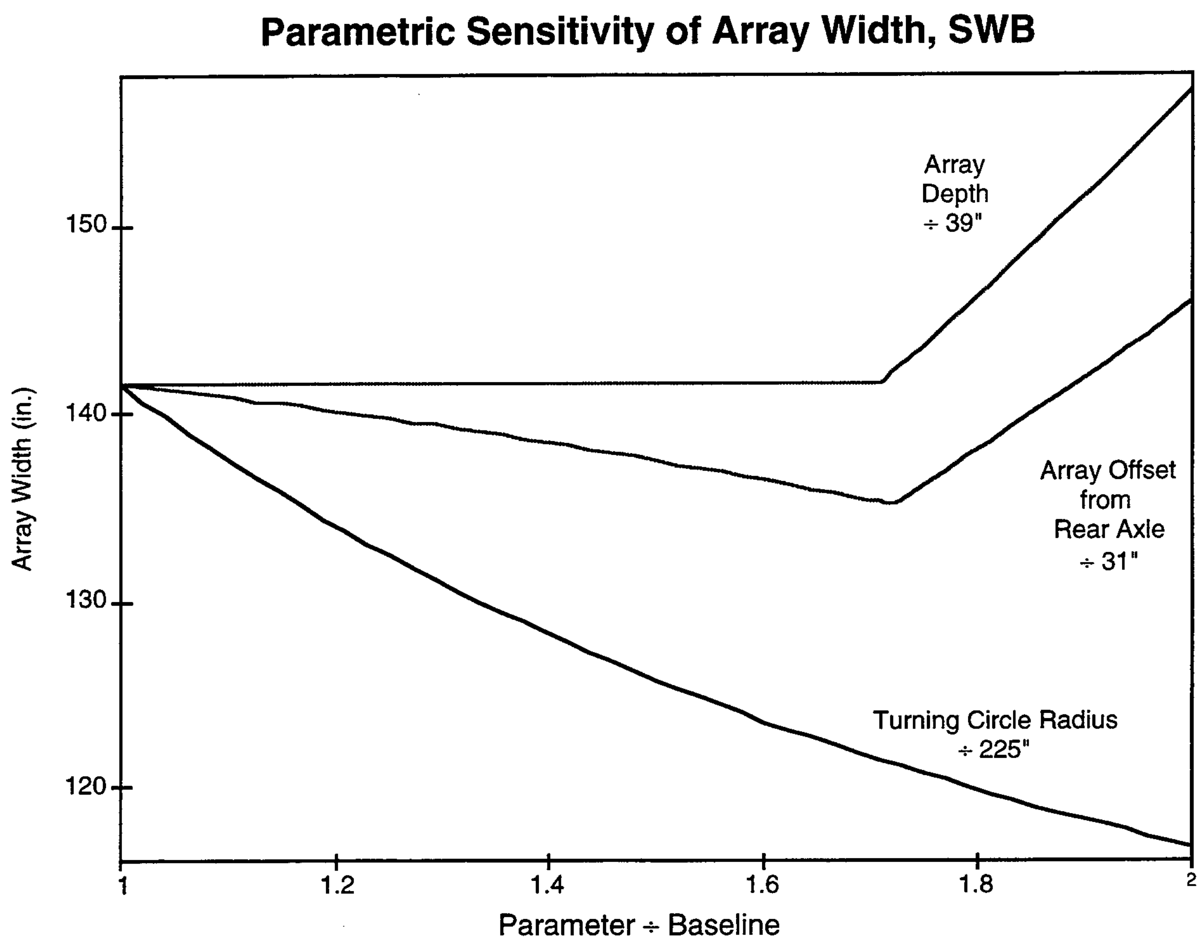
cond 2: $|\overline{\Omega A2}| < |\overline{\Omega Vi}|$

Steered Wheels Forward (SWF)

* Note that the drawing depicts an unsafe condition, violating condition 2



Steered Wheels Forward (SWF)


Parametric Sensitivity of Array Width, SWB
Array Width (in.)
150
140
130
120
Array
Depth
÷ 39"
Array Offset
from
Rear Axle
÷ 31"
Turning Circle Radius
÷ 225"
1
1.2
1.4
1.6
1.8
2
Parameter ÷ Baseline

Countermine Sensitivity Plot program for Maple

This program for Maple calculates the array width required to cover the innermost and outermost wheel tracks of a turning vehicle. The boundary conditions of the two "Safe Operation" inequalities,

$$cond1\text{: } |\overline{\Omega \quad A1}| > |\overline{\Omega \quad Vo}|$$

$$\cap$$

$$cond2\text{: } |\overline{\Omega \quad A2}| < |\overline{\Omega \quad Vi}|$$

For a Steered Wheel Behind (SWB) vehicle, these conditions are expressed algebraically as

$$cond1\text{: } \sqrt{(r\_v + a\_w/2)^2 + a\_1^2} > \sqrt{(r\_v + w/2)^2 + b^2}$$

$$cond2\text{: } \sqrt{(r\_v - a\_w/2)^2 + (a\_1 + a\_L)^2} < (r\_v - w/2)$$

and evaluate to the following minimum values of array width:

$$a\_w_{cond1} = 2 * (\sqrt{(r\_v + w/2)^2 + b^2 - a\_1^2} - r\_v)$$

$$a\_w_{cond2} = 2 * (r\_v - \sqrt{(r\_v - w/2)^2 - (a\_1 + a\_L)^2})$$

$$a\_w = \max(a\_w_{cond1}, a\_w_{cond2})$$

The program varies the values of turning circle, array depth, and array offset, and plots the results in a parameter sensitivity format.

```
################################################################################
        #HMMWV-specific constants
b := 130;                                  #wheelbase, inches
w := 85;                                   #width, inches

                                           #Baseline values for independent
                                           #variables
a_1 := 31;                                 #array offset from rear axle, in.
a_L := 39;                                 #array depth, in.
r_v := 225;                                #radius of motion of rear axle center
```

```
                                                    #(45' curb-to-curb U-turn)

                                                    #calculates baseline dependent
                                                    #variable, a_w
                                                    #evaluates to a_w0 = 141.6”
c1 := evalf(2 * (sqrt((r_v + w/2)^2 + b^2 - a_1^2) - r_v));
c2:= evalf(2 * (r_v - sqrt((r_v - w/2)^2 - (a_1 + a_L)^2)));
a_w0 := max(c1,c2);

cond_r_v := proc(alpha,r)                           #subroutine to vary r_v
local r_v,c1,c2;
r_v := r*(alpha);
c1 := evalf(2 * (sqrt((r_v + w/2)^2 + b^2 - a_1^2) - r_v));
c2:= evalf(2 * (r_v - sqrt((r_v - w/2)^2 - (a_1 + a_L)^2)));
result := max(c1,c2)/a_w0;
end;

cond_a1 := proc(alpha,a1)                           #subroutine to vary a_1
local a_1,c1,c2;
a_1 := a1*(alpha);
c1 := evalf(2 * (sqrt((r_v + w/2)^2 + b^2 - a_1^2) - r_v));
c2:= evalf(2 * (r_v - sqrt((r_v - w/2)^2 - (a_1 + a_L)^2)));
result := max(c1,c2)/a_w0;
end;

cond_aL := proc(alpha,r)                            #subroutine to vary a_L
local a_L,c1,c2;
a_L := r*(alpha);
c1 := evalf(2 * (sqrt((r_v + w/2)^2 + b^2 - a_1^2) - r_v));
c2:= evalf(2 * (r_v - sqrt((r_v - w/2)^2 - (a_1 + a_L)^2)));
result := max(c1,c2)/a_w0;
end;


                                                    #plot sensitivity
plot({cond_r_v(x,r_v), cond_a1(x,a_1), cond_aL(x,a_L)},x=1..2);
```

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1997	Final

4. TITLE AND SUBTITLE
An Unmanned Ground Vehicle for Mine Detection: Systems Integration Issues and Recommendations

5. FUNDING NUMBERS
PR: 622618AH80

6. AUTHOR(S)
Haas, G.A.; Von Wahlde, R.; Vong, T.T.; Gombash, J.W.; Scribner, D.R.; Stachowiak, C.C.; Fisher, F.N. Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Weapons & Materials Research Directorate
Aberdeen Proving Ground, MD 21010-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Weapons & Materials Research Directorate
Aberdeen Proving Ground, MD 21010-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-TR-1256

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The U.S. Army Research Laboratory performed a series of pilot studies for the Countermine Division at the Night Vision and Electronic Sensors Directorate concerning how a mine-detection sensor suite might be implemented on a teleoperated unmanned ground vehicle (UGV). The studies addressed five areas: mobility, human factors, radio communications, the use of infrared cameras for remote driving, and options for attaching the sensor array to the UGV. This report describes the proposed countermine system, the issues identified by the studies, and recommendations concerning how such a system might be implemented.

14. SUBJECT TERMS
countermine — unmanned ground vehicle
UGV and robotics

15. NUMBER OF PAGES
40

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102